THE IMPORTANCE OF MOISTURE CONTROL IN THE PROCESSING OF BITUMINOUS AGGREGATE MATERIALS

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The facts uncovered by this laboratory investigation disproves common ideas concerning oil and water. These concepts have been based on superficial observations that have with years of repetition become traditional.

Observations in field control led to this discovery. When surreptitious use was made of properly moistened aggregate in bituminous mixtures, outstanding improvements in the resultant pavement behavior were frequently noted.

These field observations prompted the systematic investigations described in this report by Stephen F. Weber, which in effect says: There is a moisture content in the processing and placing of bituminous mixtures at which the greatest amount of initial stability and resistance to deterioration can be obtained with the least amount of mechanical effort.

A careful study of this Report should provide an explanation of many behavior types and construction difficulties encountered in bituminous pavements.

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The four components of pavements, mineral aggregate, asphaltic binder, air voids, and moisture are considered in this study. Moisture in pavements has been held responsible for such phenomena as stripping of asphaltic binder from the aggregate, swelling of the pavement with disruption of its structure, loss of stability when wet, and shrinking, cracking, and disintegration upon drying. By adding to the total liquid content of pavement mixture, moisture has been associated with behavior characteristics which resemble those of overly-oiled mixes.

This study was initiated for the purpose of gaining a better understanding of the mechanism of swelling and of determining the variety and extent of the influences of moisture on the physical properties of compacted bituminous mixtures. An attempt is made to correlate the behavior of materials as revealed by the volume swell test results, under various conditions, with physical characteristics concerned with the service behavior of asphaltic pavements.

CONCLUSIONS DRAWN FROM STUDY

The data collected from this investigation are considered adequate to support the following conclusions:

1. The asphalt-aggregate mixtures absorbed water and increased in volume when subjected to moisture conditions.
2. The degree of expansion (volume swell) is governed by the characteristics of the aggregate.
3. Volume swells were accompanied by disruption of the structure of compacted asphalt-aggregate mixtures with softening and loss of stability to a degree roughly proportional to the measured volume swell.
4. There is no exact correlation between water absorption and volume swell, and materials prone to swell were not successfully inhibited by waterproofing with asphalt films and dense compaction.
5. Chemical additives employed in this series of experiments were moderately effective in promoting the adhesion of asphalts to aggregates. They retarded somewhat the rate of water absorption and swelling of the compacted aggregate mixtures, but had no permanent waterproofing effects, nor did they have any appreciable influence on the final amount of absorption and swelling.
6. Asphalt-aggregate mixtures when compacted with the mineral particles already in a swelled condition, then allowed to dry, were highly resistant to swelling, softening and loss of stability by the penetration of moisture.
7. Volume swell test results, on twenty eight aggregate mixtures compacted with moisture averaged 25% of the volume swell results of the same mixtures compacted dry.

8. Aggregate mixtures compacted with moisture absorbed on average of 50% as much water as the dry compacted specimens on an 8-day immersion.

9. Specimens compacted with moisture had an approximately 10% greater dry density than similar specimens compacted dry.

10. The unconfined compression results on 22 specimens molded with moisture averaged 258% of the stabilities of the dry compacted specimens, after 8-days immersion.

11. Each asphalt-aggregate mixture had an optimum moisture content at which a maximum density is obtained for a given compactive effort.

12. The optimum moisture content for best compaction is sufficient to take advantage of the greater part of the volume swell inhibition produced by moist compaction.

13. A certain moisture content facilitates an aggregate's cold mixing with cut-back and light road oils. Mixing is not only accomplished with less effort, but better coverage is obtained with less oil. This is especially noticeable on aggregates containing aglomerations of fines since the moisture disperses the fines so they can be readily coated with oil.

14. Compacted oil mixes may swell with water absorption and lose density and stability, but upon being recompacted in the moist condition, are not as subject to swelling and the resultant deterioration as they were before being recompacted in the moist condition. (Compare column 4 and 4 A, Table 3.)

PROCEDURES AND CALCULATIONS

Aggregates and sands from various pits located throughout the state of Montana were used in these tests. For the Volume Swell and absorption test, a 100 gram sample of -10M. material was mixed with a given percentage of asphaltic material. The percentages used were such as to coat all aggregate particles when thoroughly mixed. After being mixed with asphalt, the aggregate samples were molded into two-inch diamater briquettes by a compression machine at a sustained pressure of 2000 lb.sq.in. for a two-minute period. Some briquettes were molded under 500 lb. per. sq. in. for comparison purposes, and to more nearly approach densities obtained in actual roadway construction. Still others were prepared with various admixtures to promote adhesion of asphalt to aggregate. A duplicate mix was prepared in each instance which contained a certain percentage of moisture which was incorporated either in the mixing operation with cut-back asphalts, or after mixing in the case of oiling with heavier asphaltic materials which required heat for mixing.

The molded briquettes were immersed in distilled water after specified curing, weighing, and measuring. They were allowed to soak for a period of 8 days at which time they were removed, re-weighed, re-measured, and subjected to a stability test. The volume of the briquettes was measured by the mercury displacement method.

Data calculated and reported include the following:

Percent volume swell $S = \frac{V2 - V1 \times 100}{V1}$

Percent water absorption $- = \frac{W2 - W1 \times 100}{W1}$

Density of briquette $d = \frac{W1}{V1}$

Percent voids in specimen $V = \frac{100\ (D-d)}{D}$

Percent saturation of voids $= \frac{(W2 - W1) - (S\ V1)}{V\ V1}$

Where $V1$ = original volume of dry briquette in c.c.

$V2$ volume of briquette after eight-day immersion

$W1$ original weight of dry briquette in grams

$W2$ weight of briquette after eight-day immersion

D theoretical maximum density of briquette if free from voids = $\dfrac{100}{\frac{A}{G} + \frac{A1}{G1}}$

A weight percent of aggregate

$A1$ weight percent of asphalt binder

G specific gravity of aggregate

$G1$ specific gravity of asphalt

The Montana Cone Bearing Test was taken on some briquettes to obtain a stability value, with the result reported as the plotted angle of work vs volume displacement in degrees. A modification of the Florida Bearing Test was also used in which the measure of bearing value is reported as the load required to rupture a briquette in compression under the one-inch plunger of the Florida Bearing Machine. The results are reported as F.B.V. in pounds per square inch.

Strip tests for the determination of the adhesion of asphalt to the aggregate were run on samples of material containing predetermined proportions of -200 M. fines. After oiling, soaking for 24 hours and agitating for fifteen minutes in a ro-tap, the oiled and stripped -200 M. fines, were separated by pouring onto a 200 M. screen. The stripped fines passed through, were collected, dried and weighed. The fines which retained their film of oil were retained on the screen.

The strip test results for the fines were reported as the percent of -200 M. material remaining coated with asphalt and which did not pass the 200 M. screen in the separation. Stripping of the coarse aggregate particles was rated as good, fair, or poor by visual inspection.

A series of test mixtures was made with aggregate #95706 and a straight-run MC-3 cut-back. Aggregate #95706 is an aggregate which showed a high value for volume swell and a poor strip test when tested by standard procedures. The aggregate contained a considerable fraction of fines (14.85% of -200 M.). Minus 40 M. material obtained from dry screening had a P.I. of zero, while the -40 M. material obtained from wet screening had a P.I. of 8.6. This would indicate that plastic fines were aglomerated into particles of larger size than the 40 M., and also probably occur as coatings on coarser fractions.

Mixtures were made both with and without additives to promote adhesion, and with and without moisture, compacted, dried, and tested as shown in table 1. The results of this series of tests seem to indicate the following:

1. Chemical additives to the oil resulted in an improvement of adhesion, but no corresponding improvement in the vol. swell results.
2. Additive "B" promoted entrance of water into compacted specimen.
3. With this particular aggregate, the dry mixing process did not result in complete coverage of the fines. The wet mixing process dispersed the plastic aglomerations and resulted in more complete coverage. The better strip results on test no's. 5, 6, 7, & 8 as compared to no's. 1, 2, 3, & 4, respectively, are attributed to better mixing and more complete coverage.
4. Oiled material that was compacted with moisture, then allowed to dry, had a very small expansion when subjected to the Vol. swell test.
5. The improvement in vol. swell results of the moist compacted samples was not due to the exclusion of moisture, since there was no corresponding decrease in void saturation. It is probably significant that swelling occurs long before the voids approach saturation.

TABLE 1

EFFECT OF ADDITIVES ON VOLUME SWELL AND MOISTURE ABSORPTION

Aggregate #95706 (-10M) oiled both dry & containing 7% moisture, with 9% straight-run MC-3 for Volume Swell tests. Minus ½" material with 6½% oil was used for strip tests.

TEST NUMBER	TREATMENT OF OIL & AGGREGATE		STRIP TEST COURSE	%-200 M REMAINING OILED AFTER STRIP TEST	% MOISTURE ABSORPTION	% VOLUME SWELL	% SATURATION OF ORIGINAL VOIDS.
1	Untreated Oil	Oiled and Compacted Dry 2000# psi	Poor	18.8	14.2	19.6	42.9
2	1% Additive "A" in Oil	"	Good	57.6	13.9	17.1	43.9
3	1% Additive "B" in Oil	"	Fair	34.0	19.1	22.3	70.7
4	½% Additive "C" on Aggregate	"	Fair	53.5	8.5	10.6	44.7
5	Untreated Oil	Oiled and Compacted with 7% Moisture	Poor	52.2	4.3	3.2	27.6
6	1% Additive "A" in Oil	"	Good	92.2	4.3	0.2	49.2
7	1% Additive "B" in Oil	"	Fair	71.4	7.2	2.0	66.7
8	1% Additive "C" on Aggregate	"	Fair	88.6	4.8	1.1	43.8

A series of tests was made on oiled mixes which had been cured for twenty-four hours with various percentages of moisture before molding. The curing process consisted of the incorporation of given amounts of moisture in asphalt mixtures and allowing to stand for twenty-four hours in a closed container. The twenty-four hour period was necessary for the absorption of the moisture by the aggregate since the aggregate particles take up moisture slowly after being coated with asphalt. The conditions prescribed for this series of tests were designed to reveal the effects of different moisture contents before compaction on the density and the stability as measured by the Montana Cone Machine. The experimental results are tabulated on Table 2, and indicate the following:

1. The stability of the freshly molded briquettes containing moisture increased with the moisture content up to about two percent moisture, then gradually declined with increased moisture contents. Excessive liquid contents are shown to be detrimental to stability and gradually overcome the initial gains in stability brought about by an increase in density.
2. Greater densities were obtained in compacted specimens with increasing moisture contents up to an optimum moisture content.
3. Stabilities of the compacted and dried specimens were very closely related to the densities.

TABLE 2

EFFECT ON DENSITIES AND STABILITIES OF OIL MIXES MOLDED WITH VARIOUS MOISTURE CONTENTS

Aggregate #94384 oiled with 8% 341 pen. asphalt. Moisture cured with various percentages of water for 24 hrs. then molded at 2000 pounds per.sq.in.

% Moisture Added To Oil Mix	Cone Angle Immediately After Compaction	Cone Angle After Drying 24-hours at 100°F.	Density After Drying 24 hrs. at 120°F.
0.0	39°44'	44°46'	1.65
1.0	42°11'	49°40'	1.70
2.0	51°24'	57°00'	1.73
3.0	43°35'	50°40'	1.73
4.0	36°29'	59°36'	1.75
5.0	33°57'	66°10'	1.79
6.0	30°34'	63°00'	1.79
7.0	25°49'	64°52'	1.78

In the following series of determinations the briquettes were molded dry, using various grades of asphaltic binder as indicated, and 500 lb. per. sq. in. compression load. The molded briquettes were weighed and measured and the dry densities computed. They were then immersed in water for a period of 8 days, then re-weighed and re-measured and the water absorption and percent swell calculated.

The same briquettes were re-inserted in the mold in their soaked condition and re-compressed, removed, dried, weighed and measured and the dry density was again computed. They were then again immersed in water for 8 days, then weighed and measured for water absorption and volume swell determinations. A modified F.B.V. test was taken on the briquettes in their final soaked condition.

RESULTS:

The test results as tabulated in table 3 seem to indicate that:

1. The moisture absorption for the series of briquettes recompacted with the moisture present from the first 8 day immersion, upon being dried and re-immersed for 8 days, again absorbed an amount of moisture very nearly equal to that of the first immersion test.
2. The volume swell was reduced an average of 89.1% by recompacting with the absorbed moisture from the first immersion present in the briquettes.
3. Densities of the moist compacted briquettes averaged 15.8% higher than the first series molded without moisture.
4. The stabilities of the re-compacted with moisture briquettes in a soaked condition, varied with the consistency of the asphaltic binders.

The tabulations on tables 4 & 5 are the results obtained on two different aggregates. A series of tests was conducted in each instance in an effort to establish any relationships that might exist between density, stability and volume swell, and the moisture content at which the specimens were molded. The results of the tests on aggregate #97157 are graphically illustrated in Fig. 1. The following conclusions may be drawn from these two series of tests:

1. Both oiled mixes exhibit an optimum moisture content at which a miximum density is obtained for the specified compactive effort. The aggregates reacted differently to moisture contents in excess of optimum in that sample #97157 lost density and stability with excessive moisture contents while #96865 did not.
2. Increasing increments of moisture are accompanied by substantial reductions in volume swell. The greater portion of the volume swell reduction is attained at a moisture content corresponding to the optimum, although some further improvement is produced by still higher moisture contents.
3. Higher stability values as measured by the modified F.B.V. and the Montana Cone Test are associated with increasing densities and decreasing volume swell results which result from compaction with moisture.

TABLE 3

Aggregate #95297

STANDARD VOLUME SWELL TEST RESULTS					RECOMPACTED MOIST AND RESWELLED			
Col.1	Col.2	Col.3	Col.4	Col.5	Col.3A	Col.4A	Col.5A	
No.	Type Oil*	% Moisture Absorbed	% Swell	Dry Density Before Immersion	% Moisture Absorbed	% Swell	Dry Density Before Immersion	Stability psi (soaked) M FBV
1	SC-3	10.1	7.8	1.767	9.17	Shrinkage 0.75	2.022	55#
2	SC-6	11.2	8.5	1.727	10.76	Swell 0.92	2.009	163#
3	303 Pen.	11.1	7.5	1.716	9.37	0.73	2.006	140#
4	196 Pen.	9.8	8.5	1.707	9.21	0.73	1.983	150#
5	60-70 Pen.	9.1	8.8	1.707	8.57	1.28	1.971	210#

* - All samples oiled with 8% oil.

TABLE 4

BEHAVIOR OF #96865 OILED WITH 6% 120-150 PEN. ASPHALT AND MOLDED

WITH VARIOUS WATER CONTENTS AT 500 LBS. PER SQUARE INCH.

% Water Added to Oil Mix	Cone Angle Immediately	Cone Angle After Drying	Cone Angle After 8 Day Immersion	F.B.V. After 8 Day Immersion	Density of Dried Briquette gr./cc.	Volume Swell 8 Day %
0	------	34°59'	7°24'	41#	1.58	8.3
1½	38°00'	43°40'	10°21'	85#	1.62	7.2
3	35°15'	48°36'	18°19'	110#	1.69	4.4
4½	21°48'	47°25'	21°24'	136#	1.74	3.8
6	18°12'	58°12'	25°35'	180#	1.73	3.4
7½	11°15'	60°31'	26°26'	185#	1.73	2.0

TABLE 5

BEHAVIOR OF #97157 OILED WITH 12½% 328 PEN. ASPHALT AND MOLDED WITH VARIOUS WATER CONTENTS AT 500 LBS. PER SQUARE INCH.

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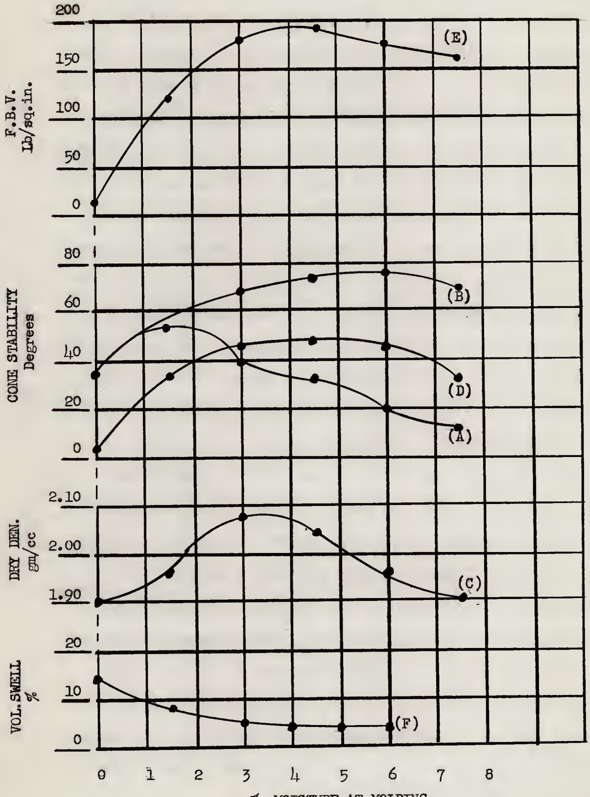
% Water Added to Oil Mix	(A) Cone Angle Immediately	(B) Cone Angle After Drying	(C) Dry Density gr./ cm.	(D) Cone Angle After 8 Day Immersion	(E) F.B.V. After 8 Day Immersion	(F) Volume Swell 8 Day %
0	34°08'	34°08'	1.90	2°15'	15#	14.5
1½	53°38'	67°40	1.96	32°16'	122#	7.8
3	38°01'	67°28'	2.08	44°52'	180#	5.3
4½	32°06'	72°49'	2.04	46°45'	192#	4.7
6	19°26'	75°10'	1.96	45°21'	175#	4.0
7½	10°58'	69°35'	1.90	31°34'	162#	3.9

Fig. 1


200
150
100
50
0
F.B.V.
Lb/sq.in.
(E)
80
60
40
20
0
CONE STABILITY
Degrees
(B)
(D)
(A)
2.10
2.00
1.90
DRY DEN.
gm/cc
(C)
20
10
0
VOL.SWELL
%
(F)
0 1 2 3 4 5 6 7 8
% MOISTURE AT MOLDING

Test results on different aggregates are tabulated in tables 6 to 12 inclusive. The same asphaltic binder was used for all mixtures, a 207 pen. asphalt. The aggregates were chosen so as to represent a full range, intermediate and low volume changes upon immersion.

The data includes the moisture content when molded, the dry density, moisture absorption and percent volume change on 8-day immersion and stability of the soaked specimen. In addition, the air voids of the dried, molded briquettes were calculated, and the saturation of the voids determined after 8 days immersion. The saturation of voids is calculated on the assumption that the moisture absorbed is taken up by the specimen in two ways. The increase in volume of the briquette, or swelling, and the filling of original voids. The volume of water assumed to enter the voids is in effect taken as total volume absorbed less the the volume increase. The accuracy of the voids saturation results are probably not comparable to the other test results, on account of the accumulation of errors, and magnification thereof in the extended calculations employed.

In table 6, the first five specimens were immersed for only 24 hours, but under 22 inches of vacuum, the remaining six specimens were given the regular 8 day soaking period. The moisture contents at molding differ from the moisture added due to moisture loss by evaporation, and, in the case of the higher moisture contents, by squeezing out upon molding. As a result, the specimens with excess water were converted to comparable conditions of moisture in the molding process and specimens 7, 8, 9, 10 & 11, table 6 are nearly identical and may be considered as check determinations. The results obtained on specimens 7, 8, 9, 10 & 11 are therefore indicative of the degree of accuracy obtained.

RESULTS

1. Perhaps the most revealing results are the percent void saturation determinations. For the most part, they are suprisingly low, except where vacuum was employed to force the water into the voids. This would indicate that the air voids or capillaries are relatively impervious to the entrance of water and that the greater portion of the absorbed moisture was absorbed by the minerals and resulted in volume increases.

2. Moisture at the time of molding resulted in higher densities, much lower volume changes and water absorption upon immersion and higher stabilities in the soaked condition. The different aggregates conform to this in varying degrees, although all are markedly effected.

3. Aggregate mixtures with high swelling tendencies have their greatest densities at a certain optimum moisture content. Excess moisture results in decreased compacted densities. The low swelling aggregates are not as pronounced in this reaction, probably due to the fact, as tabulated in the results, that the excess moisture is squeezed out of the low swelling aggregates in compaction, It appears that the higher swelling aggregates have a greater affinity for the water and the excess is not readily squeezed out in molding.

TABLE 6
#95297 -10 M. Aggregate

No.	% Moist. Added	% Moisture	Dry Density	% Swell 8 Day	% Moisture Absorbed 8 Day	Stability After Immersion	% Voids	Saturation of Original Voids %
1	0	0	1.906	11.32	14.07*	200#	17.06	90.85
2	1	0.84	1.943	11.76	12.65*	233#	15.43	83.08
3	2	1.39	1.965	11.20	12.17*	240#	14.52	87.53
4	3	2.13	1.989	9.22	10.52*	281#	13.71	85.40
5	4	2.57	2.008	6.25	8.15*	330#	12.62	80.19
6	5	3.56	2.022	2.13	1.84	700#	12.00	13.25
7	7	4.69	2.011	2.17	2.14	690#	12.49	17.05
8	9	4.65	2.004	2.21	2.10	660#	12.82	15.60
9	11	4.67	1.996	2.26	2.23	730#	13.16	16.64
10	13	4.42	2.012	2.31	2.15	710#	12.48	16.18
11	15	4.34	2.003	1.16	2.06	730#	12.86	23.09

* - Soaked under vacuum at 22" Hg. for 24 hours.

TABLE 7
#95242 -10 M. Aggregate

1	0	0	1.925	16.48	9.95	209#	19.25	13.87
2	2	1.27	2.051	14.29	7.99	302#	13.97	15.03
3	4	2.63	2.063	7.02	4.07	507#	13.44	10.20
4	6	4.86	2.023	6.81	4.35	455#	15.14	13.14
5	8	6.48	1.980	5.96	4.74	417#	16.95	20.17
6	10	7.94	1.940	6.24	5.40	400#	18.60	22.80
7	12	8.54	1.923	6.52	5.54	390#	19.33	21.42

TABLE 8

#95378 -10 M Aggregate

No.	% Moist. Added	% Moisture	Density	% Swell 8 Day	% Moisture Absorbed 8 Day	Stability After Immersion	% Voids	% Saturation Voids
1	0	0	2.067	11.58	6.42	280#	11.84	14.50
2	2	1.19	2.099	2.12	2.54	540#	10.51	30.54
3	4	2.40	2.071	0.85	2.08	512#	11.66	29.67
4	6	2.46	2.070	1.30	2.13	475#	11.68	26.62
5	8	3.04	2.060	0.67	1.67	570#	12.13	22.83
6	10	3.06	2.062	1.36	1.71	545#	12.10	17.85

TABLE 9

#95449 -10 M Aggregate

No.	% Moist. Added	% Moisture	Density	% Swell 8 Day	% Moisture Absorbed 8 Day	Stability After Immersion	% Voids	% Saturation Voids
1	0	0	1.789	18.72	16.64	132#	23.80	46.42
2	2	1.57	1.896	12.26	10.10	263#	19.24	35.80
3	4	3.16	1.976	4.55	4.61	705#	15.74	28.97
4	6	5.33	1.956	2.92	3.66	800#	16.67	25.43
5	8	7.11	1.890	1.95	3.96	640#	19.40	28.51
6	10	7.47	1.876	2.43	4.27	610#	20.00	27.90

TABLE 10

#95465 -10 M. Aggregate

No.	% Moist. Added	% Moisture	Density	% Swell 8 Day	% Moisture Absorbed 8 Day	Stability After Immersion	% Voids	% Saturation Voids
1	0	0	1.972	3.92	4.74	350#	16.61	32.66
2	2	1.28	2.090	2.08	2.80	525#	11.61	32.48
3	4	1.82	2.095	2.09	2.74	435#	10.75	33.95
4	6	2.23	2.096	1.66	2.69	480#	11.31	35.17
6	8	2.66	2.081	1.39	2.40	530#	11.99	30.03

TABLE 11

#95296 -10 M Aggregate

No	% Moist. Added	% Moisture	Density	% Swell 8 Day	% Moisture Absorbed 8 Day	Stability After Immersion	% Voids	% Void Saturation
1	0	0	1.872	17.16	12.55	200#	20.24	31.27
2	2	1.78	1.972	15.88	9.93	275#	16.14	22.92
3	4	2.90	2.043	10.71	6.54	535#	13.09	20.24
4	6	5.26	1.990	6.77	4.71	550#	15.38	16.91
5	8	6.27	1.961	5.14	4.24	590#	16.78	18.95
6	10	6.67	1.953	5.88	4.30	570#	16.93	14.88

TABLE 12
#95314

No	% Moist. Added	% Moisture	Density	% Swell 8 Day	% Moisture Absorbed 8 Day	Stability After Immersion	% Voids	% Void Saturation
1	0	0	2.065	6.80	4.67	490#	20.41	13.91
2	2	1.80	2.121	3.62	2.93	620#	11.28	22.96
3	4	2.44	2.115	2.55	2.37	590#	11.55	21.30
4	6	3.00	2.112	2.53	2.01	640#	11.66	14.67
5	8	3.43	2.075	2.51	2.12	650#	13.39	14.12

Tables 13 to 20 present test results on the same aggregate, employing different asphaltic materials as the bituminous binder.

RESULTS AND CONCLUSIONS

1. Volume swell and water absorption results were somewhat lower for the heavier grades of bituminous binder. This is probably due to the heavier asphalts setting up a stronger internal structure which resisted somewhat the disruptive forces of the swelling aggregates. It is doubtful that it is due to waterproofing, since the lowest swelling specimens (higher moisture contents at molding) have higher void saturation than the un-inhibited (dry molded) specimens for all series of tests on this aggregate.

2. This series of tests tend to indicate that by molding the aggregate mixtures in a moist, or pre-swelled condition, the voids (after drying the mixture and shrinking the swelled aggregate particles) are fixed so that subsequent swelling and shrinking may take place, filling and emptying these voids without disrupting the structure of the compacted mixture. This conclusion is reached from the following results:

   a. The volume change of the briquettes upon soaking is greatly reduced for the specimens which were molded with moisture (pre-swelled).

   b. Stability of the specimens molded with moisture was greater after soaking than for specimens molded dry, indicating less breakdown of mechanical structural bonds.

   c. The voids of the specimens molded with moisture were very much more saturated after soaking than those of the dry molded materials indicating that the swelling took place within the structure of the moist molded specimens and filling the voids, not outwardly which would have increased the volumes of the specimens, disrupted their structures and reduced their stabilities as it did in the case of the dry molded mixtures.

TABLE 13

#92938 - 10 M Aggregate

Type of Oil	No.	% Moisture at Molding	Density	% Swell 8 Day	% Moisture Absorbed 8 Day	Stability After Immersion	% Voids	% Void Saturation
No Oil	1	0	1.710					
	2	3.62	1.873					
	3	7.37	1.958					
	4	9.22	2.000					
	5	10.59	1.980					

TABLE 14

Type of Oil	No.	% Moisture at Molding	Density	% Swell 8 Day	% Moisture Absorbed 8 Day	Stability After Immersion	% Voids	% Void Saturation
SC-4 10% of Mix	1	0	1.768	26.54	17.13	15#	22.62	16.57
	2	1.91	2.054	22.11	11.36	58#	10.12	11.95
	3	4.36	2.012	7.99	6.25	132#	11.96	38.30
	4	7.32	1.926	5.83	7.22	123#	15.70	51.40
	5	10.02	1.848	4.74	8.08	96#	19.11	53.33

TABLE 15

Type of Oil	No.	% Moisture at Molding	Density	% Swell 8 Day	% Moisture Absorbed 8 Day	Stability After Immersion	% Voids	% Void Saturation
MC-3 10% of Mix	1	0	1.834	35.62	22.63	14#	18.02	32.68
	2	1.72	1.937	28.82	17.72	31#	15.25	36.06
	3	3.01	2.042	18.14	11.00	112#	10.63	40.65
	4	5.31	1.992	8.88	8.18	149#	12.80	57.89
	5	8.02	1.908	5.21	8.32	153#	16.50	64.60

TABLE 16

#92938 - 10 M Aggregate

Type of Oil	No.	% Moisture at Molding	Density	% Swell 8 Day	% Moisture Absorbed 8 Day	Stability After Immersion	% Voids	% Void Saturation
RDS-2 10% of mix.	1	0	1.879	28.70	16.96	28#	17.77	17.78
	2	1.74	1.969	21.49	12.71	81#	13.81	25.63
	3	3.03	2.036	10.53	7.43	188#	10.91	42.16
	4	5.78	1.961	5.21	6.09	250#	14.17	47.49
	5	4.08	1.906	4.08	6.68	240#	16.57	52.20

TABLE 17

150-200 Pen. Asph. 10% of Mix	1	0.00	1.801	20.88	12.19	127#	21.2	5.05
	2	2.05	1.993	18.18	9.67	320#	12.8	8.50
	3	3.49	2.020	8.75	6.61	486#	11.8	39.00
	4	5.62	1.981	6.95	6.46	473#	13.3	44.00
	5	7.82	1.917	5.81	6.82	362#	16.1	45.15

TABLE 18

RC-2 10% of Mix	1	0	1.907	22.26	12.75	102#	16.54	12.33
	2	2.05	2.035	16.98	9.49	115#	10.97	21.24
	3	3.12	2.044	6.98	4.45	347#	10.57	20.00
	4	4.73	1.991	1.22	3.76	325#	12.85	48.71
	5	6.68	1.936	1.43	3.62	282#	15.29	36.49

TABLE 19

60-70 Pen. Asph 10% of Mix.	1	0	1.739	17.19	10.66	222#	23.88	5.65
	2	1.59	1.916	13.50	7.05	498#	16.14	0.00
	3	2.81	1.981	8.38	5.76	610#	13.33	22.73
	4	3.60	1.989	5.81	5.13	537#	12.93	33.95
	5	6.45	1.913	6.12	5.91	436#	16.28	31.81

TABLE 20

#92938 - 10 M. Aggregate

12% SS-1 Emulsified Asphalt

No.	% Moisture at Molding*	Density	% Swell 8 Day	% Moisture Absorbed 8 Day	Stability After Immersion
1	0	1.680	27.97		30#
2	1.10	1.850	26.39	17.12	92#
3	1.20	1.900	24.34	14.03	98#
4	2.70	2.020	10.10	6.20	370#
5	6.13	2.000	4.08	6.18	315#
6	8.80	1.890	5.41	7.21	285#
7	9.50	1.870	4.41	6.81	215#
8	12.20	1.770	2.55	6.18	118#
9	14.41	1.740	2.70	6.31	150#
10	14.49	1.730	2.70	6.07	167#
11	15.75	1.730	5.47	7.96	166#
12	16.10	1.730	5.05	5.71	170#

* 22-25% moisture used to obtain a smooth mix, then dried to the moisture contents shown before compacting.

On table 21, is tabulated the volume changes upon soaking for 8 days of a variety of aggregates. The columns headed Routine Volume Swell contain the percent increase in volume and soaked stability of the aggregates with no moisture present at molding.

The Oiled Moist, Compacted Moist columns list percent swell results for the aggregates which were mixed in a moist condition (cold mixed with liquid asphaltic materials) and molded in the moist condition.

The Oiled Dry, Compacted Moist columns contain the results of percent swell and soaked stability for the dry aggregate, bituminous mixtures which were moistened 24 hours before molding.

Although the bituminous binders employed were not of the same type and grade for all aggregate samples, the series of tests on each sample as numbered represent the results for the same grade, type and source of bituminous material.

TABLE 21

DESCRIPTION			ROUTINE VOLUME SWELL		OILED MOIST	OILED DRY COMPACTED MOIST.	
Lab. No.	Project	Grade of Oil Mix	% Swell	Stability Soaked psi	COMPACTED MOIST % SWELL	% SWELL	Stability (Soaked) psi
85075	F 328 E (PC)	RCS-2	10.72		2.4		
92938	328 (14)	150-200	20.88	127#		5.81	362#
"	"	RC-2	22.26	102#		1.95	282#
"	"	60-70	17.19	222#		5.81	537#
"	"	RCS-2	28.70	28#		4.08	240#
"	"	MC-3	35.62	14#		5.21	153#
"	"	SC-4	26.54	15#		4.74	96#
92939	FHP 53-B	RCS-2	20.06		2.0		
"	"	SC-4	22.3		4.6		
94209	S 41 (3) PC	300 Pen	14.69			0.10	
94562	S 12 (4) PC	MC-3	14.28	115#	2.3	3.60	302#
94565	"	MC-3	5.17	133#	1.2	1.40	330#
94568	S 323 (7) PC	MC-3	12.40	118#	5.1	4.50	294#
94725	S 32 (2) PC	MC-3	6.27	140#	1.6	1.40	390#
94726	"	MC-3	8.49	FBV89#	2.0	1.30	330#
94730	"	MC-3	11.0	115#	1.6	2.70	329#
94823	FAP 157 C PC	MC-3	11.53	75#	3.8	3.6	394#
95224	S 15 (4) PC	SC-4	9.22	117#	1.5	1.6	300#
95225-9	S 15 (3)&(4)	SC-4	11.50			2.90	
95242	FAP 117 A(PC)	207 Pen	16.48	209#		5.96	417#
95296	S 8 (7) PC	207 Pen	17.16	200#		5.14	590#
95297	"	MC-3	10.87	112#	2.0	3.3	320#
"	"	207 Pen	11.32	200#		1.16	730#
95314	FAP 117 A (PC)	207 Pen	6.80	490#		2.51	650
95378	F 95 (PC)	207 Pen	11.55	280#		0.67	570#
95449	PRA 32	207 Pen	18.72	132#		1.95	640#
95465	FI 67 (5) PC	207 Pen	3.92	350#		1.39	530#
95706	Research 1610	MC-3	19.6		3.2		

REVIEW AND ANALYSIS

Comparison and study of the amount of water absorption and vol. swell, stability, density and voids of the different aggregate-bituminous mixtures under the conditions of test reveals a pattern for moisture absorption and swell. The absorbed moisture increases the size, or swells the aggregate particles, and varies from about $1\frac{1}{2}$ to 6 or 7% moisture for the different aggregates tested. These figures are the amounts of moisture that were necessary to completely pre-swell the aggregates, and are considered as absorbed moisture from that standpoint.

In addition to the moisture absorbed by the aggregate particles themselves, an additional amount of water is allowed to enter the swelling specimen because of the disruption of particle alignments and asphaltic bonds and creation of new voids. Further, the swelling and disruption apparently increase the size of some of the original voids, removes structural blocks to these voids and thereby results in increased saturation of the original voids. The aggregate mixtures having high water absorption and volume increase, with accompanying disruption of particle bonding and alignment, lose stability and crack and disintegrate upon drying and shrinking.

When the same aggregate-bituminous mixtures are compacted with moisture, the reactions of the specimens to water absorption and its effects is altered. If the mineral particles prone to swell are allowed to absorb moisture and satisfy their affinity for water before compaction, the individual particles are molded into the specimen in their largest volume state. The structure of the mass, particle alignment and bituminous bonding is then fixed under that condition of maximum volume for all particles. Upon drying, the swelled particles shrink, leaving small voids encompasing each shrunken particle.

Subsequent wetting and drying of the particles then results in the particles' swelling and shrinking within the pre-formed voids. In this way, they do not increase the total volume of the mass by disrupting structural bonds, and therefore do not produce large values for volume swells as measured in this investigation. Since no great volume change and breakdown of structure occures, the specimens tend to maintain their stability with soaking.

Theoretically, it should be possible to eliminate volume changes altogether with complete pre-swelling of the aggregates. Actually, for the materials tested, an average of about 80% reduction in volume swells was obtained by the use of moist compaction. One factor tending to prevent the total elimination of volume increases may be that the pressures used in compaction are sufficiently high to partially compress and dehydrate the swelled particles so that they are not compacted in their state of largest volume. Also, an aggregate containing a small percentage of high swelling minerals might react differently from an aggregate with an equal volume change but which is composed almost entirely of moderately swelling minerals.

Waterproofing, as a factor in the elimination of volume change and stability loss, by permanent exclusion of moisture was of no discernable significance for the bituminous-aggregate mixtures employed in this investigation.

There does not appear to be any definite limiting value for the volume swell which could be set as a standard to insure against detrimental action of water. Some aggregates soften and lose more stability with a given volume swell than do others. It appears that the immersion-compression test, or a variation thereof, as used in this investigation, is a better measure of resistance to deterioration from swelling. If desired, the influence of stripping can be approximately evaluated by employing an effective additive for promoting

adhesion and comparing the volume swell, water absorption and stability loss of the mixture with one not containing the additive. This can be verified approximately by estimating the effect on stability loss from the volume swell (since they correlate quite well with a given aggregate), or by minimizing the effects of volume swell with moist compaction and comparing results.

Since the volume swell is shown to have a great influence on the condition of specimens, its determination in a dry compacted mixture and also a moist compacted mixture is of great significance in the evaluation of the effects of moisture on the behavior characteristics of pavements. Since all pavements (shoulder sections possibly excepted) eventually are subjected to moist compaction by natural precipitation and traffic, the reaction of the pavement materials to this treatment is significant in the evaluation of the materials and in the setting of the specifications.

Failure of shoulders of pavements or other non-traffic sections to receive this conditioning treatment may offer an explanation for some types of pavement deterioration.

If the mechanism of swelling is substantially as developed in this report, there appears to be no reason why the principles involved could not be employed to advantage in subgrade compaction. Indications are that a soil subject to large volume changes could be at least partially inhibited by compacting with excess moisture (excess over optimum) to lower densities. It also follows that efforts to compact these soils to maximum densities may not only be wasted, but may induce a condition of greater susceptibility to deterioration by excessive volume changes.

The various influences of moisture on the properties of bituminous mixtures as presented in this investigation have been magnified by employing only the -10M. fraction of aggregate, except in a few

instances of 10% sand aggregates. While this is sufficient for the identification of influences and tendencies, the grading of the whole aggregate must be taken into account in order to properly evaluate the net effect.

It would seem probable that the characteristics of the -10M. aggregate might be reflected to a lesser degree on pavement constructed with an open textured aggregate. The construction methods may also exert some influence upon the carrying through of certain characteristics to the finished pavement. It is known that for road mixed pavements, moisture assumes an important role since it is present in significant amounts either before, during, or after construction and that the pavement is in a favorable condition to respond to traffic compaction for an extended period. Hot mixed, hot-laid pavements expecially when bound with harder asphalts are more likely to resist the kneading action and compaction of traffic with moisture. This would tend to prevent the natural rearrangement of aggregate particles and formation of a structure which would accomodate the particles in their largest volume, or swelled condition.

While this may not be construed as vindicating the use of inferior aggregates in the lower type cold mixed pavements, it should warn against their use in hot mixed type pavements. It tends to indicate at least that the hot mixing with penetration asphalt of an inferior aggregate is not a panacea for a poor aggregate and that the resulting pavement may even be inferior in some respects to the cheaper cold mixed pavement.

It has been found in field practice that the partial elimination of the finer size fractions from an aggregate from a certain source greatly improves the resistance to deterioration from moisture.

Sometimes the dilution of the natural fines with manufactured or crusher fines results in improvement, and in some instances the opposite. The character of the fines as measured by the P.I. has been found to be unreliable as any indication of susceptibility to moisture deterioration of bituminous aggregate mixtures. This may be due to various other factors overshadowing the effects indicated by the P.I. and that the worst offending minerals are not always confined to the finest aggregate fractions that produce plasticity.

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